High Sensitivity Pressure Sensors Utilizing Advanced Polymer Coatings

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Abstract

We report a high sensitivity pressure sensor utilizing optical fibers coated with novel polymers. Pressure sensitivity of 5 pico-m/psi for the fiber Bragg grating based and −155 dB radian/μPa for interferometric sensor is reported.

Introduction: Since the early days of fiber optic sensors there has been significant interest in utilizing specialty coatings on fibers to develop compact, low cost sensors [1]. While there has been wide spread activity in developing coatings which are sensitive to specific measurand, progress in this field has been hampered either by the lack of sensitivity provided by most coatings or by the lack of practicality of applying certain types of coatings on fibers. To circumvent this problem, researchers have successfully developed transducing elements, which are highly sensitive to a given measurand. For instance, the use of air-backed mandrels with varying amounts of optical fiber in an interferometric geometry has led to the development of practical, high sensitivity acoustic sensors (e.g. hydrophones) which are field tested and are currently in industrial production [2]. While such sensors are practical and mature there is still significant interest in reducing the size and production cost of these sensors. Therefore in order to provide the next generation of high performance, compact, low cost sensors there is still substantial interest in developing fiber optic sensors utilizing coated fibers. In this work, we report for the first time, the use of a special type of polymer coating which allows for a fiber sensor with pressure sensitivity which is at least an order of magnitude better than any other polymer material reported so far. The temperature responsivity of the coating is also reported. The polymer coating was configured both in a Michelson interferometer arrangement and a Bragg grating arrangement.

Advanced Polymer Material: The polymer used in this work is a type of a polyurethane. The primary difference between standard polyurethane and the material used in this work concerns the addition of micro-balloons as part of the polymer matrix [3]. It is the use of these micro-balloons, which function as tiny air pockets within the polymer matrix, which makes the material highly compressible thus resulting in extremely high pressure sensitivity compared with other polymers. Such materials, sometimes known as pressure release materials, undergo large displacements as a function of applied pressure. The compressibility of a pressure release material is directly proportional to the density of the micro-balloons in the matrix and can result in volumetric changes of 45%. An optical fiber embedded in such a material should be able to measure the strain created in the material. Due to the severe differences between the moduli of the optical fiber and the polyurethane material, only a fraction of the induced strain in the material is expected to be transferred to the optical fiber.

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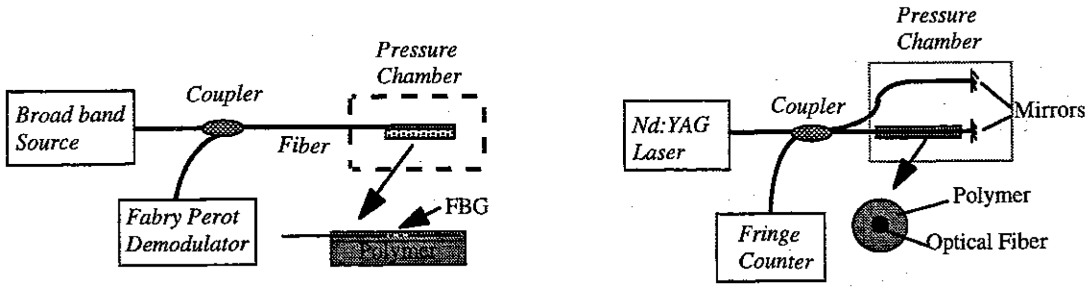

Figure 1. Experimental arrangement for (a) FBG based polymeric coating pressure sensor, and (b) polymer coated fiber in a interferometer geometry for pressure sensing.

In this work, we measure the pressure and temperature responsivity of an optical fiber embedded in an advanced polymer matrix containing 13% micro-balloon density. The measurements are carried out using an optical fiber embedded in a sample of the aforementioned advanced polymer, which is subsequently subjected to hydrostatic pressure and temperature cycling. The transduction mechanism of the device (i.e. optical fiber plus the polymer) is measured using two methods: a) a fiber Bragg grating (FBG) is placed inside the polymer and the wavelength shift of the FBG detected as a function of applied pressure and temperature and (b) a polymer coated fiber is made part of a Michelson interferometer and the phase shift detected as a function of applied pressure. The pressure transducer is fabricated by bonding an FBG on the surface of a rectangular piece (5 cm x 1 cm x 1cm) of the pressure release polymer material and then over-coated with a thin layer of polyurethane (Figure 1a). The wavelength shift in the FBG due to the strain in the material is detected using a standard scanning Fabry-Perot wavelength detection scheme [4]. The nominal wavelength of the FBG was near 1.3 μm. The interferometric transducer is fabricated by cutting a cylindrical piece (diameter = 3 mm, length = 20 cm) from a similar polymer pressure release material and then inserting the optical fiber through the center of the polymer cylinder, thus creating a coated fiber. The fiber was made part of a Michelson fiber interferometer and the signals were analyzed with a quadrant counting demodulator to give an output proportional to the phase shift in the interferometer (Figure 1b).

Results: Figure 2 shows the response of the micro-balloon impregnated polymer material containing the FBG along with the response of a bare FBG to a hydro-static pressure and temperature cycle. The data clearly shows that the pressure and temperature responsivity of the FBG, which is embedded in the pressure release material is significantly higher than that of the reference(bare) FBG. In fact, 500 pounds-per-square-inch (psi) hydro-static pressure results in wavelength shift of greater than 2 nano-meter (nm) and a change of 80 °C in temperature results in a wavelength shift of greater than 5 nm. A simple linear fit of the data shows that the pressure sensitivity of the transducer is approximately 5 pm/psi and temperature sensitivity is about 70 pm/°C. The FBG spectrum showed no degradation in terms of spectral broadening throughout the experiment. The hydrostatic pressure cycle also shows a mechanical hysteresis associated with the material, which is not uncommon for polymers and has been observed in other polymers in the past [1].

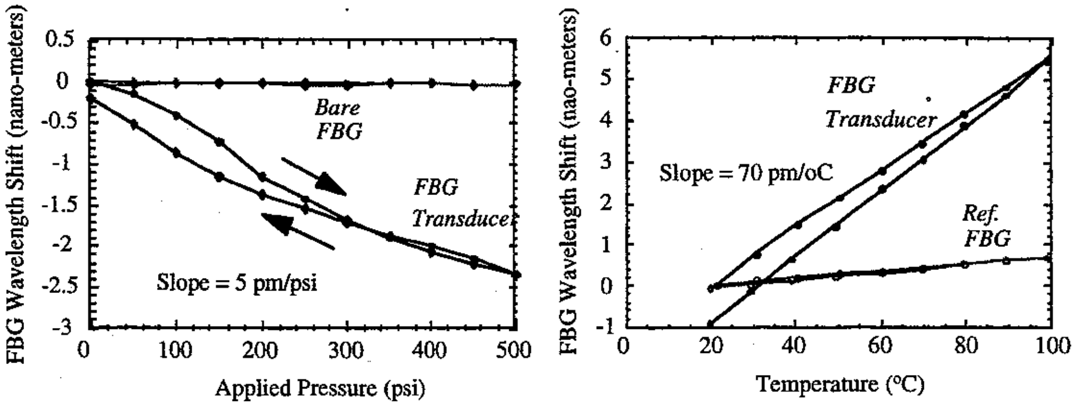

Figure 2. Measured FBG wavelength shift as a function of applied hydrostatic pressure and temperature cycling.

The pressure sensitivity reported here is at least an order of magnitude higher than that of previously reported coated fiber based pressure sensors and also easily surpasses the pressure sensitivity of reported FBG based mechanical pressure transducers [5]. Utilizing wavelength shift detection schemes capable of resolving sub micro-strain in static and quasi-static frequency regimes [4], it should be possible to develop pressure sensors with dc and low frequency resolution of better than 0.1 psi using the type of polymer coating reported here. Analogously, dynamic pressure signal resolution of better than 10^{-4} psi/$\sqrt{Hz}$ should be possible using a interferometric wavelength shift detection scheme [4]. Table 1 compares the sensitivity of various FBG based pressure transducers and clearly shows that micro-balloon based polymers have one of the highest pressure responsivity of all the pressure sensors reported so far. Such materials have great potential for providing a high sensitivity coated FBG pressure sensor. In order to develop static and quasi-static FBG based pressure sensors, which incorporate advanced polymers described in this work, the temperature sensitivity of the materials must be compensated. This could be accomplished by utilizing two gratings embedded in the polymer material with one of the two gratings isolated from pressure signals. Such sensors could be very useful for a variety of Naval (e.g. general purpose pressure monitoring in ships) as well as non-Naval applications (e.g. oil well industry). Extensive temperature compensation may not be required if the primary goal is to make dynamic pressure measurements, which is of great interest for a variety of reasons including underwater acoustics. Numerous laboratory measurements have shown that the DC responsivity of the material is maintained at least up to several kilo-Hertz. Arrays of high sensitivity coated optical fiber dynamic pressure sensors could be utilized for measuring in-air acoustic as well as for monitoring seismic activity on the ocean floor and elsewhere.

Table 1 – Comparison of Pressure and Temperature Sensitivity of FBG Transducers

Sensor [Ref.]	**Pressure Sensitivity**	**Temperature Sensitivity**
Bare FBG [5]	0.04 micro-strain/psi	9 micro-strain/°C
Typical Polymer (e.g. Nylon) [1]	0.2 micro-strain/psi	N/A
Mech. Transducer [5]	0.15 micro-strain/psi	6 micro-strain/°C
Micro-balloon Based Polymer	5 micro-strain/psi	70 micro-strain/°C

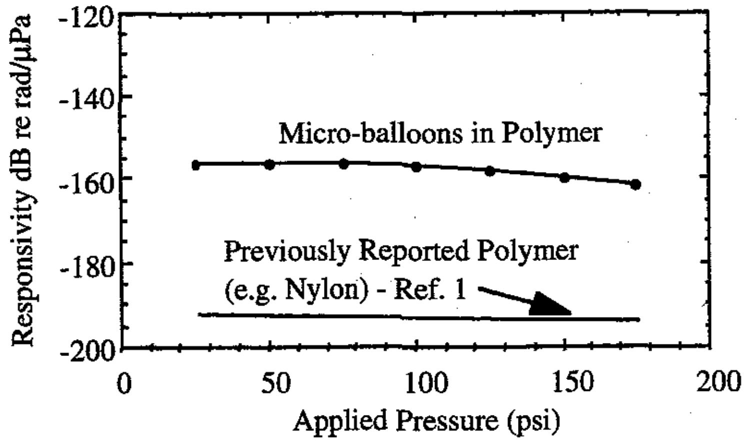

Figure 3. Response of micro-balloon based polymer coated fiber interferometric pressure sensor. To convert from micro-Pascal to psi, use 145 psi = 1 Mega-Pascal. The data shown is for a sensor gauge length of 20 cm.

In order to measure the sensitivity of the coating in an interferometric arrangement for potential use in underwater acoustics, measurements were made in the arrangement shown in Figure 1b. The results of that measurements are summarized in Figure 3. It is customary to show the results of interferometric pressure sensors in radians/μ-Pascal. It is clear from Figure 3 that the responsivity of the novel micro-balloon based polymer is several orders of magnitude better than that of previously reported pressure coatings, which is consistent with the FBG measurements shown in Figure 2 and Table 1. A micro-balloon based polymer coated fiber interferometer has the potential to provide acoustic signal resolution comparable to the best fiber optic acoustic sensors based on mechanical transducers (e.g. mandrel based sensors. [2]). For instance, interferometers with phase resolution of –110 dB re radians/√Hz at 1 kHz are routinely made, which in conjunction with high sensitivity polymer coated fiber pressure sensor described in this work can provide acoustic resolution of better than 50 dB μPa/√Hz at 1 kHz. Such sensors would be highly desirable for many underwater acoustics applications.

Conclusions: We have described novel, micro-balloon based polymers ideally suited as coating materials for high performance fiber optic pressure sensors. The coating displays higher pressure sensitivity than any other polymer coating previously reported. For dc and low frequency pressure measurements, its temperature sensitivity must be taken into consideration. The coatings also have great potential to provide high resolution dynamic pressure (i.e. acoustic) sensitivity for numerous applications.

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